Multi-diagnostics of the onset of formation of nanoparticles in a pre-mixed laminar flame

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The generation mechanism of nanoparticles in combustion has been widely studied in the recent years, due to the large implications that particulate has for the environmental protection and for the human health [1]. These researches were widely investigated in the automotive field [2,3], and very few works have been performed for industrial combustors [4,5]. Moving from automotive to industrial combustors (gas turbine, furnace, boilers) implies an upgrading of the measurement techniques in the field of time and space resolution to follow the dynamic structure of the phenomena and on the field of sensibility for the low concentration of particles below 10 nm. To achieve these efforts is necessary to use different experimental techniques and to adapt them to the specific investigated conditions, because nowadays there isn't a technique that could combine all those required characteristics.

The aim of the project was to set up a diagnostic system suitable to combustion conditions characterized by high turbulence, spatial and time non homogeneity, elevated characteristic frequencies (up to tens of kHz) and low particles concentration. To achieve this goal we performed a simultaneously application of a sampling technique, Scanning Mobility Particle Sizer (SMPS), and three optical techniques (spectral light emission, laser induced incandescence and light extinction) for the detection of nano-particles produced during the combustion process in a 20kWatt test burner.

A 6-cm, water cooled, McKenna burner was used to generate laminar premixed ethylene-air flames at different equivalent ratio, ϕ, defined as the ratio between the air fed and the stoichiometric air, and different cold unburned gas velocity. The flame was shielded from the surrounding atmosphere by a shroud of nitrogen A stainless steel plate was set 30mm above the burner to stabilize and protect the upper part of the flame. The set up of all the diagnostic system, on a well-known burner [6-7], allowed to characterize both techniques behaviour and particle inception phenomenon.

All the techniques chosen gave complementary information about particles produced in the flame. Spectral light emission could detect the threshold of nanoparticles generation, SMPS performed number distribution and concentration of particles in a defined flame region, LII gave spatial distribution of particles and light extinction gave the line sight volume fractions. A comparative analysis of the results for the different techniques in terms of sensitivity on capability to reveal the onset of particle formations was performed. Moreover was studied how the particles inception was influenced by ϕ and cold gas flow rate.

Increasing the ϕ, the flame colour turned from blue to yellow, which are considered respectively a non-sooting and a sooting flame. The optical emission seemed to be the most sensible technique to evaluate particles inception, but it couldn't give information about particle density and size. LII, laser extinction and SMPS gave information about particle density, in terms of volume fraction for each techniques and number only for SMPS, this last one gave also information about particle size. LII gave also information about the spatial particle distribution, and it individuated the flame region where particles were located, which will be very important in a turbulent flame.

Measurements were performed for ϕ at different cold gas flow rates (5, 7 and 10 cm/s). For each gas velocity and for each technique was individuated a threshold of the equivalent ratio (ϕ_{thres}) as the ϕ beyond which the measured signal showed a sudden increase. The Φ_{thres} was calculated as the abscissa of the interception of the two different slope asymptotic lines in logarithmic scale. The ϕ_{thres} depended on the cold unburned gas velocity particularly it increased with the growth of cold gas flow rate, maybe due to the higher flame temperatures obtained increasing gases flow rate [8].

The volume fraction of the particles measured by the optical extinction was compared to the ones derived from SMPS measurements for a cold gases flow rate of 7 cm/s. A very good agreement was obtained in the ϕ range between 1.8 and 2.0. The lower value was individuated by laser extinction due to the low sensibility of the technique, the higher value of f was determined by SMPS because for ϕ bigger than 2 there were some blockage problems in the sampling system, due to the high particles concentration.

In conclusion the comprehension of the combustion phenomena, and particularly the process of particles generation in the flame, requires the measurement of different parameters, such as particle size distribution and volume fraction, which are spatially dependent within the flame. In this work, we showed that the simultaneous use of different diagnostic techniques can provide a complete characterization of the spatial distribution of the particles in the flame. The results obtained are coherent and promising in view of a shift towards industrial burners.

References

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P.4 Multi-diagnostics techniques for Nanoparticle Characterization in premixed gas combustion

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A diagnostic system suitable to combustion conditions characterized by high turbulence, spatial and time non homogeneity, elevated characteristic frequencies (up to tens of kHz) and low particles concentration especially for fuel lean combustion, was set up. To achieve this goal we performed a simultaneously application of a sampling technique, Scanning Mobility Particle Sizer (SMPS), and three optical techniques (spectral light emission , laser induced incandescence and light extinction) for the detection of nano-particle produced during the ethylene air combustion in a 6-cm, water cooled, McKenna burner with a maximum thermal power of 20kWatt.

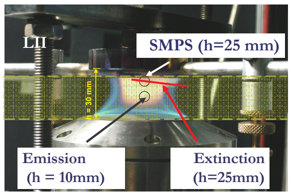


Fig.1 - The McKenna burner and the diagnostics used

The optical signal coming from a central region of the flame (about 6 mm diameter, fig.1) was conjugated on the entrance of an optical fibre coupled to a mini-spectrometer. The system provided the optical emission spectrum between 250 and 800 nm. The presence of the particles was evidenced by their black body emission, that is more relevant in the right region of the spectrum, for wavelength $\lambda \geq 500$ nm (fig.2, Optical Emission).

Number particle size distributions (PSDs) and volume fractions were performed by sampling aerosol from the flame at fixed height above the burner (25 mm) and analyzing it by TSI Model 3936 Scanning Mobility Particle Sizer (SMPS). The sampling and dilution system consisted of an horizontal stainless steel tube of 9 mm internal diameter with an orifice of 0.4 drilled in its bottom and the sampled aerosol were diluted by a nitrogen flow near the probe tip. The collected sample was analyzed by the SMPS instrument, which allowed the classification of particles in the size range between 3 and 1000 nm and the measurement of number concentrations between 20 and 10^7 particles/cm^3.

Visible imaging gave a first evidence of the presence of nanoparticles in the flame.

Figure 2 shows a phenomenological comparison of the outputs of the diagnostics used, for different values of the flame equivalent ratio (Φ, fuel/stoichiometric fuel) at a fixed value of the cold gas velocity (v = 7 cm/s). Increasing the ϕ, the flame colour turned from blue to yellow, which are considered respectively a non-sooting and a sooting flame, and this change was followed by all the techniques used. Similar behaviour was observed for others values of cold gasses flow rates (5 and 10 cm/s)

VISIBLE IMAGING | OPTICAL EMISSION | SMPS | LII | EXTINTION

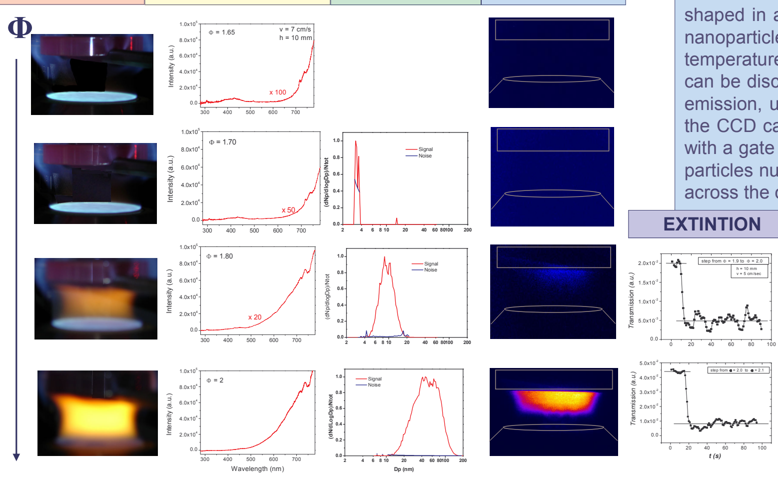


Figure 2 - Phenomenological overview of the nanoparticles formation with the growth of Φ

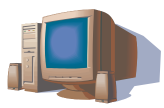
The beam emitted by a Nd-YAG laser at 532 nm, shaped in a light sheet configuration (fig.1), heated the nanoparticles slightly below the carbon vaporization temperature. The black body emission of the particles can be discriminated from the lower temperature flame emission, using a low-pass filter at 450 nm and setting the CCD camera to acquire 50 ns after the laser pulse, with a gate of 50 ns. The LII signal is proportional to the particles number density, giving a 2D spatial distribution across the central section of the flame.

A He-Ne CW laser beam was sent horizontally through the centre of the flame (fig.1). The attenuation of the laser beam, caused by absorption and scattering by the particles was measured. This attenuation was calculated from the changes in the laser transmitted intensity in passing from the condition of a lean flame (low Φ) to the one of interest. This quantity is proportional to the volume fraction of the nanoparticles in flame.

... from the phenomenological observation to the measurement:

WHAT IS THE SIGNAL TO BE MEASURED?

Integral intensity collected in the range 670-690 nm	**Particles number density and size dispersion**	**Integral intensity in the area irradiated by laser**	**Changes of the transmitted intensity at varying Φ**



RESULTS

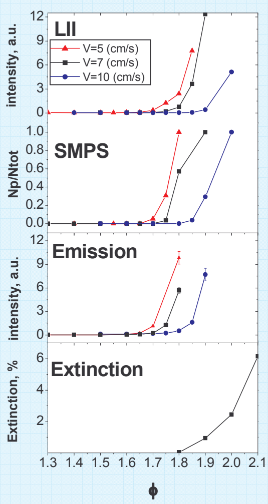


Figure 3 - Measured signals vs. Φ for three velocities of cold gases

The signals of the four different techniques are shown in figure 3 as a function of ϕ for three different cold gas flow rates.

At each fixed value of the cold gas velocity, and for each technique was individuated a threshold of ϕ as the value beyond which the measured signal showed a sudden increase. The threshold value Φ_{thres} was defined as the abscissa of the interception of the two asymptotic lines. Thresholds for the four different techniques are compared in fig.4. The ϕ_{thres} depended on the cold unburned gas velocity, and it increased with the growth of cold flow rate.

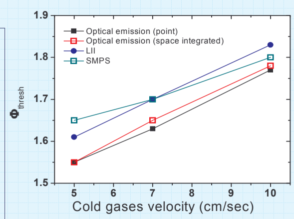


Figure 4 - Thresholds vs. v

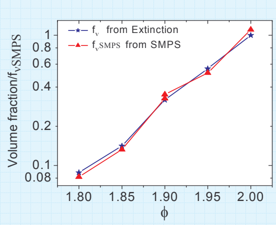


Figure 5 - Volume fraction vs. Φ

In fig.5 the volume fractions of the particles measured by the optical extinction is compared to the ones derived from SMPS measurements for a cold gases flow rate of 7 cm/s. A very good agreement was obtained.

CONCLUSIONS

A comparison of the sensitivity of the different techniques was performed and a formation threshold in ϕ_{thres} was individuated. This threshold increased with the velocity of the cold gases, as shown in fig.4. All the techniques here considered are able to reproduce the same trend of Φ_{thres} with cold gases velocity. The different sensitivities of the various diagnostics and the different information that they provide confirm the need for a multi-diagnostics setup and suggest a measurement protocol for the characterization of nanoparticles formation. The optical emission can be used to individuate the early stage of particulate formation, while the other techniques provide more quantitative information. LII can be used for reconstructing the spatial distribution of the nanoparticles, extinction provides their volume fraction and SMPS the number size distribution.